Aerosol Observability and Data Assimilation Investigations in Support of Atmospheric Composition Forecasts

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LONG-TERM GOALS

In this 2nd year of a 3 year effort by the Naval Research Laboratory Code 7544 to enable Navy aerosol forecasting to take full advantage of available data feeds through the investigation of fundamental atmospheric composition observability, we find that the next generation of data feeds and associated technology present a number of challenges and opportunities which require attention. These include: 1) The transition from NASA EOS sensors to the next generation of diversified operational and near real time data sources; 2) The move to a constellation approach for global atmospheric composition observing, 3) The expected near real time availability of US and European lidar data; 4) The enhanced availability of surface and aircraft observations, and 5) Increased aerosol model demands for such applications as joint surface-atmosphere retrievals, directed energy (DE), and intelligence, surveillance, and reconnaissance (ISR). This increase in the number of potential data sources, coupled with further efficacy demands, creates an imperative need to understand the nature of global aerosol observability and the development of realistic uncertainties for composition observations, retrievals and model products. Outstanding problems facing the community relate to such issues as observation bias, representativeness, and information spreading for the myriad of sporadic data sources available. To meet this need, we propose to investigate the use of these diverse flows of data using ensemble and ensemble data assimilation technologies to be incorporated into the Navy Aerosol Analysis and Prediction System (NAAPS)/Navy Variational Analysis Data Assimilation-Aerosol Optical Depth (NAVDAS-AOD) framework.

OBJECTIVES

Our overarching goal is to ultimately investigate applied science aerosol observability issues related to the proper determination of observed product efficacy and information spreading. To this end the core methodology involves the development and application of an ensemble version of NAAPS and its subsequent ensemble based data assimilation system. Subcomponents include;

1) The development of an ensemble-based NAAPS system which makes use of the FNMOC NOGAPS ensemble data set: Here we will use the base NAAPS model, including the data assimilation system and run in parallel with the 20 NOGAPS fields, further perturbed with 10

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to 30 additional perturbations to source and sink functions. This version of NAAPS will be prepared for eventual transition to 6.4 and FNMOC if the Navy so desires.

2) The development of key verification metrics of models and observations alike: Based on initial simulation of the ensemble, we will investigate appropriate error metrics for Navy satellite and model products that account for the non-Gaussian, spatially correlated nature of biases present in the environment. This objective includes the development of probabilistic tools for forecasts. These can then be applied to satellite observations for model verification.

3) Investigation into the nature of available satellite and in situ observations including their flow dependant correlation lengths for use in NAVDAS-AOD: The optimal mix of meteorological and source/sink perturbations for the NAAPS ensemble for given computational constraints will be identified. A particular emphasis will be on the application of these methods to aerosol vertical distribution.

4) The incorporation of NAAPS in the NCAR Data Assimilation Test-bed (DART): Once the NAAPS ensemble model is running quasi-operationally and is well understood, we will port NAAPS to the DART package at NCAR. This is the first step in developing our ensemble-based data assimilation system.

5) The creation of a research grade ensemble-based data assimilation system: Based on our experience with the DART system, we anticipate being able to have the ability to harvest and develop a robust ensemble based data assimilation system. This will be used to supplement the existing 3DVAR aerosol data assimilation system currently in use. Emphasis in this system will be on sparse or isolated observations such as provided by lidars, sun photometers and surface reports. In addition, ensemble co-variability studies will be carried out to address phenomenological questions such as modes of atmosphere/aerosol coupling.

6) Collaborate with other centers to derive an aerosol consensus for severe events: It has been shown that for many extreme events, consensus forecasting is a top performer. In this objective we wish to investigate the applicability of performing multi-model consensus of GMAO, ECMWF and other centers to investigate the predictability and extent of significant aerosol events.

APPROACH

Work performed in FY12 focuses on the development of an ensemble based data assimilation system for NAAPS. Spatial covariance fields are generated in an ensemble version of NAAPS (henceforth eNAAPS). Nominally eNAAPS is run quasi-operationally using the 20 NOGAPS ensemble members generated by FNMOC every 12 hours. Additionally, other members, based on perturbations to the NAAPS source function, can be created. The selection process, i.e. how these draws will be made, is critical. On one hand, we could simply scale all source functions +/- some percent; this would maximize correlation lengths and ultimately influence plumes at the continental scale. On the other hand, performing draws on the 6 hourly model time step will shorten correlation lengths to individual event levels. Establishing the proper balance of draws coupled with the computational cost of each model simulation will require a great deal of back-and-forth negotiations between model development and the analysis components of the project. This balance will also drive computer and storage requirements procured under this grant.

Adequate tools and display system are also developed. Basic tools for analyzing ensemble variably, correlation length scales, and the most commonly employed “spaghetti plots” were largely adapted from existing Matlab code into Perl, Python and IDL framework currently used in 7544 and FNMOC. Online verification products based on AERONET, satellite data and own analysis are being developed. In a similar manner to eNAAPS, we cooperate with other meteorological centers over the globe which are developing global aerosol prediction capabilities. By pulling data from such centers as ECMWF, JMA, NASA GMAO, and NOAA NCEP, we created a first of its kind global aerosol multi-model ensemble. For comparison purposes, products generated are similar in nature to eNAAPS.

While we view this first half of the development component to be straightforward, beneficial to Navy needs and of very low risk, the bulk of the effort in years two and three will be towards the much higher risk/reward ensemble based data assimilation effort. The Japan Meteorological Agency (JMA) and its funded researchers have made significant progress in the application of Ensemble Kalman Filter (EnKF) to aerosol modeling. Due to the extensive lidar network maintained by the Japanese National Institute for Environmental Studies (NEIS), coupled now with space based CALIOP lidar data, the Japanese have a solid observing system for the assimilation of major dust and pollution outbreaks with a particular emphasis on boundary layer aerosol particles. This capability is in line with many US Navy needs and should be applied. Our course of action is to port NAAPS into the NCAR *Data Assimilation Research Testbed (DART).* DART hosts numerous ensemble–based data assimilation tools including the core components of an EnKF system. Both NOGAPS and COAMPS have already been ported to DART and in fact ensemble based COAMPS dust source functions studies are already underway under a joint project with Dr. Hansen. Hence, in house knowledge already exists to expedite this process. Included in this budget is additional travel money so that NRL developers can spend the required time at NCAR to make this port happen.

Finally, verification tools need to be generated to evaluate improvements to the model. This not only allows model parameterizations to be investigated and improved, but also the satellite data assimilated into the models. In particular, technologies need to be created that can quickly evaluate new or updated satellite products, such as being generated by VIIRS.

WORK COMPLETED

In FY 12, the following tasks were completed:

1) An ensemble based aerosol optical depth data assimilation system was generated using the NCAR *Data Assimilation Research Testbed (DART).* First data runs were evaluated.

2) Both eNAAPS and the ICAP multi-model ensemble were run quasi-operationally for the fiscal year. Data was distributed for of both on web portals.

3) New ensemble products were generated, including a threat score

4) Online verification tools have been generated for scoring of both deterministic and ensemble products. This includes the development of a baseline climatology and persistence model (CLIPPER) to be used across operational centers.

RESULTS

Research results for this project can be divided into areas of ensemble development, verification, and data assimilation.

Ensemble Development: 7544 continues to develop collinearly both the eNAAPS single model and ICAP multi-model ensembles. Data for eNAAPS is available to the general public via the 7544 website (http://www.nrlmry.navy.mil/aerosol/NAAPS_ens.php), whereas distribution of the multi-model ensemble continues to be limited to just the production centers. New products generated include a threat score, for eNAAPS, and a consensus plot for ICAP. An example of a consensus product is presented in Figure 1, where warning areas for different models are plotted with a threshold of aerosol optical depth>0.6. Individual model threats are plotted, with overlapping colors signifying consensus. The problem with this method is that each model has its own set of AOD biases. Hence, a newer version was also in development in FY12 which anonymously plots the fraction of models which identify a 1 sigma event- thus normalizing out large scale biases in the models.

Verification: Key to the ensemble system development is verification, which is underway at the aforementioned distribution websites. Not only can such verification be used to evaluate the models, but also the data being assimilated into them. Hence, parallel eNAAPS runs were made quasi-operationally assimilating different satellite data sets. An example product is given in Figure 2. Here we show an example day of AOD from a run in which we assimilated both MODIS and AVHRR data. The lower panel shows the difference of this assimilated model run from February 1, 2012. In addition to the multiple data assimilation runs, progress was made in the development of a Climatological-persistence forecast baseline model (e.g., CLIPER) to allow for unified verification across different centers. We are currently iterating with centers to develop the climatological AOD baseline. The time constant was determined to be regionally dependent based on the climatological AOD, with higher AODs having longer time constants.

Data Assimilation: A draft version of the DART Ensemble Kalman Filter (EnKF) data assimilation system has been ported to eNAAPS and run for a two week test period in May 2011. An example output file is presented in Figure 3. There, the posterior AOD analysis is given for May 2, 2011 after MODIS AOD fields were assimilated into the model with the new EnKF system. In the lower plot, the difference is computed against the current 2D var version of AOD assimilation used by FNMOC. Over most of the globe, the results are identical. However, in regions of strong AD gradients, such as at frontal boundaries in Saharan Africa and East Asia shown here, there are very strong differences. Whereas the current 2D var version is univariate (i.e., spreads information in an e fold decay of 250 km), the ensemble system spreads the information in a flow dependent way. This means that information can be spread over a greater area from more isolated AOD observations.

IMPACT/APPLICATIONS

We expect much of this work to be of immediate use to the warfighter. Just as the current NRL aerosol page is frequently used in the METOC community, we expect these ensemble products to be of immediate applicability. To begin with, in key portions of the globe we can generate dust, smoke, or pollution "Spaghetti plots" for each of the meteorological members (Figure 4) or independent models. These can also be shown spatially as areas of high variability (Figure 1c). In these areas we will collaborate with Dr. Hansen who is working on METOC impacts, decision aids, and scorecards.

TRANSITIONS

We have begun discussions with FNMOC to transition eNAAPS to operations.

RELATED PROJECTS

This project is tightly coupled to a number of ONR 32 programs, particularly those of Professor Jianglong Zhang at the University of North Dakota. Our primary transition partner is Douglas Westphal, who is principal investigator on the Large-Scale Aerosol Model Development (PI: Doug Westphal). New data-processing and visualization systems are being adapted for aerosol research through the COAMPS-On Scene(COAMPS-OS®)[1] IVPS charts program (PI: John Cook). We have also begun working with Jim Hansen on his ONR -funded project for the use of ensemble data assimilation in the prediction of atmospheric constituents.

PUBLICATIONS

Journal Publications

Campbell, J. R., J. S. Reid, D. L. Westphal, J. Zhang, J. L. Tackett, B. N. Chew, E. J., Welton, A. Shimizu, N. Sugimoto (2012), Characterizing aerosol particle composition and the vertical profile of extinction and linear depolarization over Southeast Asia and the Maritime Continent: The 2007-2009 View from CALIOP, Atmos. Res., in press.

Eck, T. F., B. N. Holben, J.S. Reid, D. M. Giles et al., (2012), Fog- and cloud-induced aerosol modification observed by the Aerosol Robotic Network (AERONET), J. Geophys. Res., 117, D07206, doi:10.1029/2011JD016839.

Hyer, E. J., J. S. Reid, E. M. Prins, J. P. Hoffman, C. C. Schmidt, J. I Miettinen, L. Giglio, (2012), Different views of fire activity over Indonesia and Malaysia from polar and geostationary satellite observations , *Atmos. Res.,* in press.

Shi, Y., J. Zhang, J. S. Reid, E. J. Hyer, T. F. Eck, B. N. Holben, R. A. Kahn (2011): A critical examination of spatial biases between MODIS and MISR aerosol products – application for potential AERONET deployment, Atmos. Meas. Tech., 4, 2823–2836, doi:10.5194/amt-4-2823-2011.

Shupe, M. D., V. P. Walden, E. Eloranta, T. Uttal, **J. R. Campbell**, S. M. Starkweather, M. Shiobara, Clouds at Arctic atmospheric observatories, Part I : occurrence and macrophysical properties, *J. Appl. Meteorol. Clim., in press, November 2010.*

Other Publications

Campbell, J. R., J. L. Tackett, J. S. Reid, J. Zhang; D. L. Westphal, M. Vaughan; David M. Winker; Ellsworth J. Welton, J. M. Prospero; A. Shimizu, N. Sugimoto (2011), Evaluating CALIOP nighttime Level 2 aerosol profile retrievals using a global transport model equipped with Two-Dimensional Variational data assimilation and ground-based lidar measurements Abstract A52D-04 presented at 2011 Fall Meeting, AGU, San Francisco, Calif., 5-9 Dec. 2011.

[1] COAMPS-OS® is a registered trademark of the Naval Research Laboratory.

Campbell, J. R., J. Zhang, J. S. Reid, D. L. Westphal, W. R. Sessions, A. Benedetti, E. J. Welton (2012), Aerosol lidar profiling and data assimilation for operational global mass transport modeling and visibility forecasting, Abstract S2O-05 presented at the 26th International Laser Radar Conference, Porto Heli, Greece, 25-29 June, 2012.

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Hyer, E., J. S. Reid, D. L. Westphal, W. R. Sessions, J. Zhang, R. S. Johnson, M. Christensen, X. Liang, A. Ignatov, First-look diagnosis of satellite aerosol optical depth retrievals using a data assimilation system, 18th Conference on Satellite Meteorology, Oceanography and Climatology/ First Joint AMS-Asia Satellite Meteorology Conference, American Meteorological Society Annual Meeting, New Orleans, LA, 22-26 Jan. 2012.

Hyer, E.J., D. L. Westphal, J. S. Reid, J. Zhang, J. R. Campbell (2012), Satellite observations for Air Quality applications. Presented at 2012 Aerosol and Atmospheric Optics Conference: Visibility and Air Pollution Symposium, Whitefish, Montana, 24 -28 Sept. 2012.

Johnson, R. S.,_, J. Zhang, J.S. Reid, E. J. Hyer, J. R. Campbell, D. L. Westphal, W. Sessions (2011) The impact of multi-sensor satellite aerosol products on aerosol data assimilation in the NAAPS model Abstract A53C-0357, presented at 2011 Fall Meeting, AGU, San Francisco, Calif., 5-9 Dec. 2011.

Reid, J. S., J. R. Campbell, L. Di Girolamo et al. (2011), A critical examination of aerosol observability in the clean marine environment, Abstract A24A-01 presented at 2011 Fall Meeting, AGU, San Francisco, Calif., 5-9 Dec. *Invited*

Reid, J.S., J. R. Campbell, D. Hegg, K. Kaku, W.C. Keene, E. Lewis, A.Smirnov, T.D. Toth, A. Van Eijk, J. Zhang, Coarse mode marine aerosol particles: A brief review. Presented at 4th annual International Cooperative For Aerosol Prediction, Frascati, Italy, May 16-20, 2012

Schmidt, C. C., E. M. Prins, E. Hyer, J. P. Hoffman, J. Brunner, J. S. Reid (2012), The Global Geostationary Wildfire ABBA: Current Implementation and Future Plans, 18th Conference on Satellite Meteorology, Oceanography and Climatology/ First Joint AMS-Asia Satellite Meteorology Conference, , American Meteorological Society Annual Meeting, New Orleans, LA, 22-26 Jan, 2012.

Shi, Y., J. Zhang; J. S. Reid, B. Liu; R. Deshmukh (2011). Multi-sensor Analysis on Data-Assimilation-Quality MISR Aerosol Products_Abstract A53C-0358, presented at 2011 Fall Meeting, AGU, San Francisco, Calif., 5-9 Dec. 2011.

Toth, T. D., Y. Shi, J. Zhang, J. R. Campbell, J. S. Reid. A Multi-Sensor Analysis of Satellite Aerosol Optical Depth Retrievals Over the Southern Oceans, Abstract A53C-0363, presented at 2011 Fall Meeting, AGU, San Francisco, Calif., 5-9 Dec. 2011.

Toth, T. D., Y. Shi, J. Zhang, J. R. Campbell, J. S. Reid (2012). A Satellite Analysis of Aerosol and Cloud Properties Over the Southern Midlatitude Oceans, 18th Conference on Satellite Meteorology, Oceanography and Climatology/ First Joint AMS-Asia Satellite Meteorology Conference, American Meteorological Society Annual Meeting, New Orleans, LA, 22-26 Jan, 2012.

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Zhang, J., J. S. Reid, J. R. Campbell, E. J. Hyer, D. L. Westphal, Y. Shi, R. S. Johnson, and N. L. Baker (2012), Development of a Multi-Sensor Aerosol Data Assimilation Method From MODIS, MISR, and CALIPSO Aerosol Products for Operational and Climate Applications, 18th Conference on Satellite Meteorology, Oceanography and Climatology/ First Joint AMS-Asia Satellite Meteorology Conference, American Meteorological Society Annual Meeting, New Orleans, LA, 22-26 Jan, 2012.

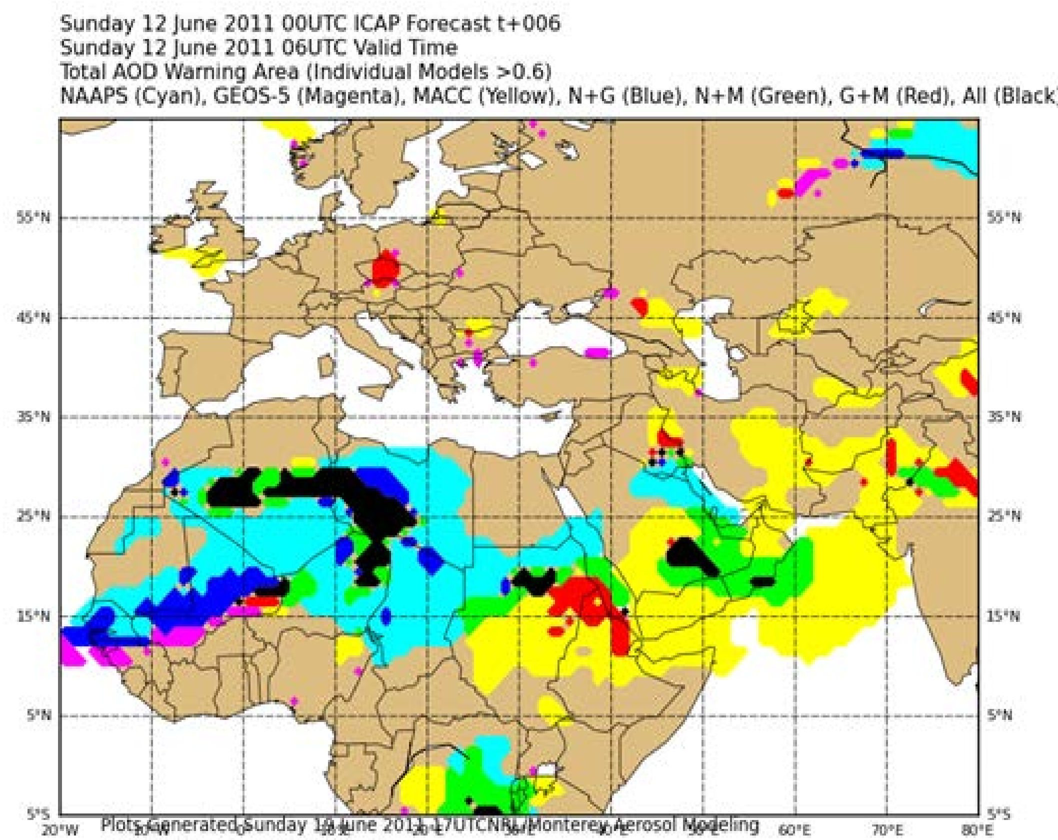

Figure 1. An example consensus product showing a threat score for AOD>0.6 for the Navy NAAPS (cyan), the NASA GEOS-5 (magenta) and the ECMWF MACC (yellow) models. When threats overlap, NAAPS+GEOS-5 is blue, NAAPS+ MACC is green, GEOS-5+MACC is red, and all is black.

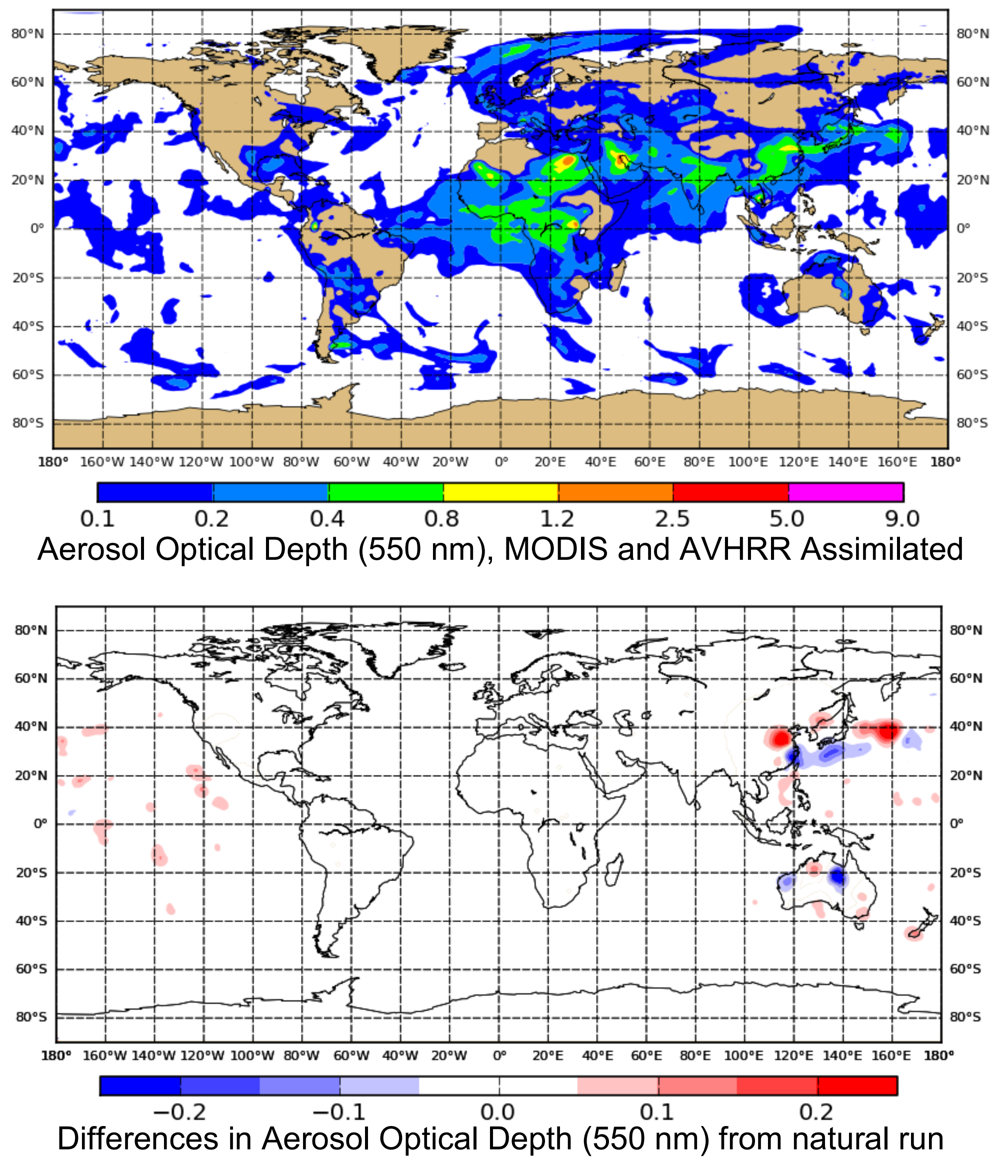

Figure 2. Upper: Aerosol Optical depth for February 1, 2012, where both MODIS and AVHRR data were assimilated. Lower: Difference of this run from the natural run with no data assimilation.

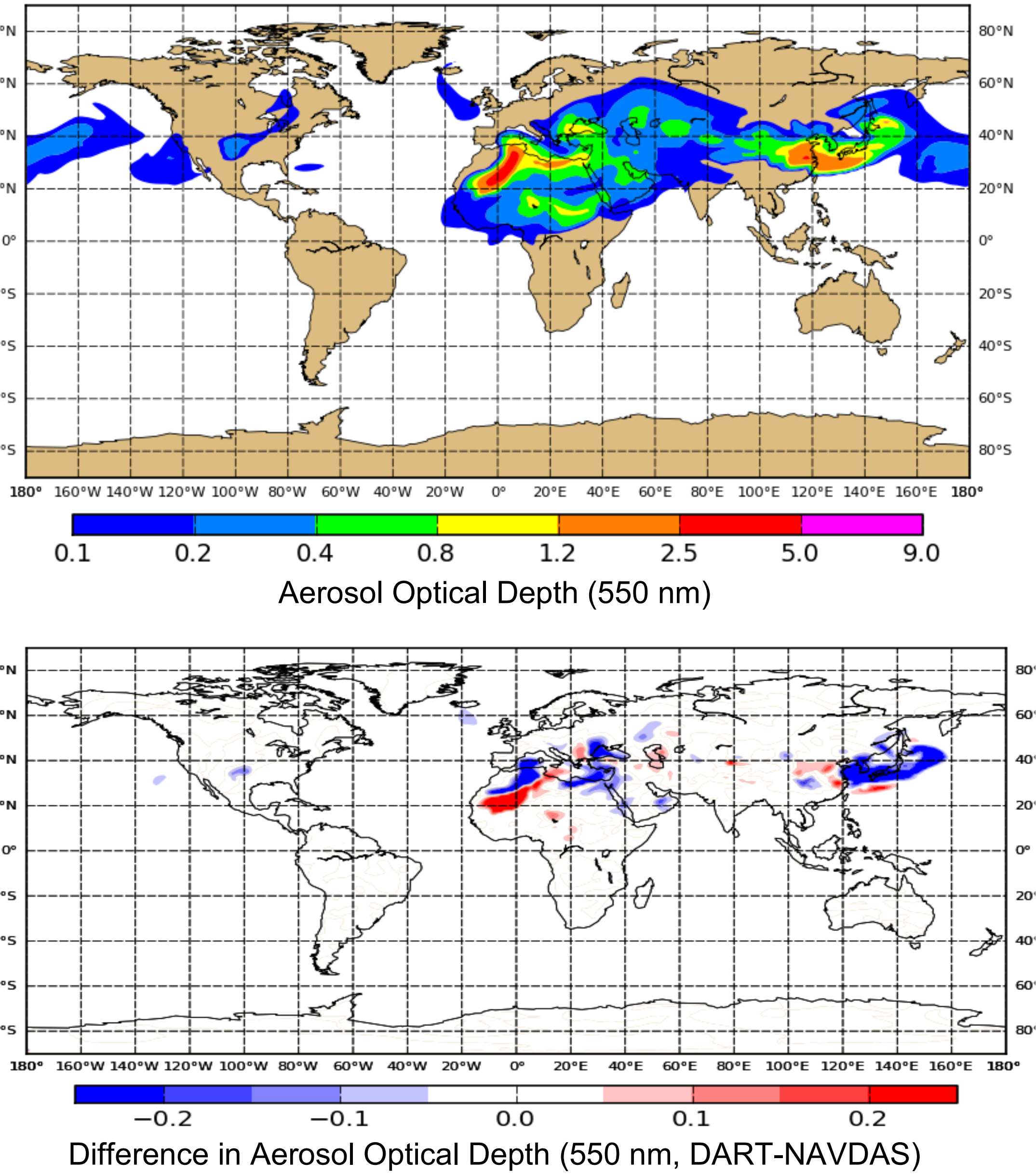

Figure 3. Upper: A DART Ensemble Kalman Filter (EmKF) AOD analysis between eNAAPS and MODIS AOD. Lower: Difference between the above analysis and the baseline 2D var assimilation run used at FNMOC. Notice the large flow dependent differences in frontal regions in Saharan Africa and East Asia.